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Microplastics in Freshwater: A Global Review of Factors Affecting Spatial and Temporal Variations

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Microplastics in freshwater: A global review of factors affecting spatial and temporal variations☆

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ABSTRACT

Microplastics are a pollutant of growing concern, capable of harming aquatic organisms and entering the food web. While freshwater microplastic research has expanded in recent years, much remains unknown regarding the sources and delivery pathways of microplastics in these environments. This review aims to address the scientific literature regarding the spatial and temporal factors affecting global freshwater microplastic distributions and abundances. A total of 75 papers, published through June 2021 and containing an earliest publication date of October 2014, was identified by a Web of Science database search. Microplastic spatial distributions are heavily influenced by anthropogenic factors, with higher concentrations reported in regions characterized by urban land cover, high population density, and wastewater treatment plant effluent. Spatial distributions may also be affected by physical watershed characteristics such as slope and elevation (positive and negative correlations with microplastic concentrations, respectively), although few studies address these factors. Temporal variables of influence include precipitation and stormwater runoff (positive correlations) and water flow/discharge (negative correlations). Despite these overarching trends, variations in study results may be due to differing scales or contributing area delineations. Thus, more rigorous and standardized spatial analytical methods are needed. Future research could simultaneously evaluate both spatial and temporal factors and incorporate finer temporal resolutions into sampling campaigns.

1. Introduction

Plastic production has increased dramatically in recent years, with some estimates of production rates topping 330 million tons per year (Jiang et al., 2019). While plastics such as microbeads are manufactured at very small sizes, larger plastics can degrade over time due to a host of environmental variables (Eerkes-Medrano et al., 2015), often becoming categorized as microplastics. While a standard definition of microplastics has yet to be agreed upon, many studies have included an upper and lower limit of 5 mm and one micron, respectively (Horton et al., 2017).

Microplastics are a growing concern in aquatic environments, impairing water quality and damaging organisms that ingest them (Eerkes-Medrano et al., 2015; Li et al., 2020a). The majority of early microplastics research focused on their abundance in marine environments, with the earliest studies published in the 1970s (Carpenter and Smith, 1972; Colton et al., 1974). The focus on microplastics in freshwater environments is a relatively recent phenomenon, with the first studies published only within approximately the last fifteen years. Microplastics have quickly become a ubiquitous pollutant; indeed, it is not uncommon for freshwater research to observe and report microplastics at all sampling sites, and often in all collected samples (Liu et al., 2020; Shruti et al., 2019; Yin et al., 2020).

This expansion of the research focus to include freshwater is a critical one, as rivers are now known to play a key role in the transportation of microplastics (Hu et al., 2020; Klein et al., 2015; Rodrigues et al., 2018), particularly to marine environments (Jiang et al., 2019; Zhao et al., 2019). It was recently estimated that the Nakdong River in South Korea contained an annual load of between 53.3 and 118 tons of microplastics in 2017 (Eo et al., 2019), many of which wind up in ocean environments. In fact, recent riverine microplastic flux calculations indicate that marine microplastic concentrations may even exceed previous estimates (Hurley et al., 2018). We cannot fully comprehend the existence and abundance of microplastics in ocean waters if we do not also understand their transportation pathways and land-based sources.

In addition, the majority of microplastics are generated by land-

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based anthropogenic activities, and can be flushed into freshwater environments through runoff processes (Horton et al., 2017). In periods of dry weather, these plastics can have extended residence times in rivers and continually degrade over time (Li et al., 2020a). In wet seasons, more extreme flows can exacerbate microplastic pollution in these water bodies and resuspend particles that had previously been trapped in sediment (Hurley et al., 2018).

While many research studies address microplastics in major rivers, there is no indication that lower order streams are less at risk for microplastic pollution. Indeed, recent findings suggest that microplastic abundances in tributaries and streams are comparable to river mainstems and other larger freshwater bodies (Dikareva and Simon, 2019; Hurley et al., 2018; Sankoda and Yamada, 2021), and may thus serve as critical transportation pathways for microplastics (Hurley et al., 2018). Freshwater microplastics research has focused on evaluating trends in quieter waters as well, including lakes, ponds, and wetlands (e.g., Bertoldi et al., 2021; Su et al., 2016; Wang et al., 2017). These still waters can be substantially affected by microplastic pollution present in contributing streams and rivers (Migwi et al., 2020). As shown in Fig. 1, a greater number of the reviewed studies collected samples in running water bodies (e.g., streams, rivers) rather than in still waters (e.g., lakes, ponds). Few studies sampled both types of water bodies.

It has become increasingly important to analyze microplastic pollution from both spatial and temporal standpoints, as these factors serve as the drivers of the distribution and abundance of microplastics in freshwater bodies (Stanton et al., 2020). In particular, land cover and proximity to anthropogenic activities are critical components of freshwater microplastic pollution, with microplastics originating from a broad range of terrestrial sources (Grbić et al., 2020). It is also necessary to examine how such land-based sources are transported to freshwater environments, and to understand the role of temporal factors such as the timing and volume of precipitation and runoff in these delivery pathways. Once in an aquatic environment, microplastics are subjected to hydrodynamic processes, which may influence their accumulation or deposition (de Carvalho et al., 2021; Mani and Burkhardt-Holm, 2020).

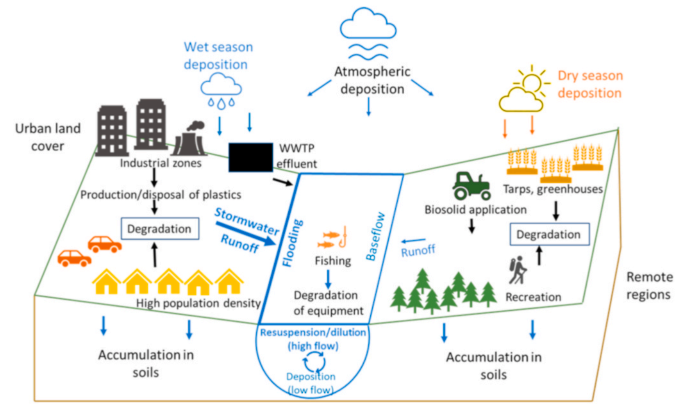

Fig. 2. Spatial and temporal factors influencing the distribution and abundance of freshwater microplastics (adapted from Lintern et al., 2018 and Horton et al., 2017).

Fig. 2 outlines these components of the microplastic cycle, with a particular focus on anthropogenic sources of microplastics and the processes that influence their introduction to and distributions within freshwater bodies. A thorough understanding of these components is crucial to the development of microplastic flux estimates of a water body (Eo et al., 2019; Xiong et al., 2019).

Recent reviews of freshwater microplastics have focused on topics including procedures for analyzing and detecting microplastics (Dris et al., 2015; Gong and Xie, 2020; Koelmans et al., 2019; Zhang et al., 2020), impacts of microplastics on organisms (Li et al., 2020a, O'Connor et al., 2016), differing microplastic sampling procedures (Eerkes-Medrano et al., 2015; Horton et al., 2017), microplastics in water versus sediment samples (Szymanska and Obolewski, 2020) and primary versus secondary production (Akdogan and Guven, 2019; Eerkes-Medrano et al., 2015). While some reviews have included discussions regarding

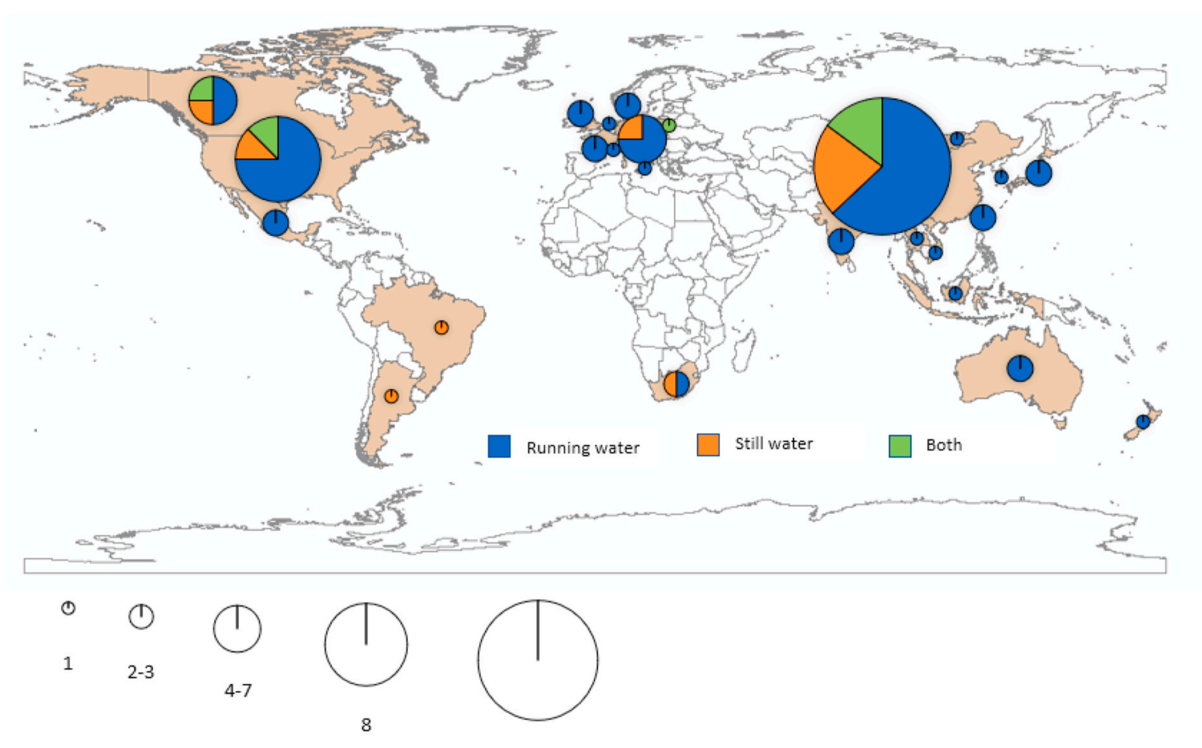

Fig. 1. Global distribution of the selected freshwater microplastic publications as a function of whether samples were collected from running water (e.g., rivers, streams), still water (e.g., lakes), or both. The numbers shown refer to the number of publications in a particular size category.

microplastics and land-based sources, (Eerkes-Medrano et al., 2015; Horton et al., 2017), few have provided a more in-depth focus on the broad range of spatiotemporal factors affecting microplastic pollution. Thus, the current review aims to expand and build upon this knowledge base by providing an overview of the spatial and temporal factors affecting microplastic abundances in freshwater environments, and by evaluating watershed attributes and hydroclimatic variables that affect microplastic pollution.

Different studies use different scales of analyses, which may affect findings and conclusions drawn regarding potential microplastic sources or the microplastic cycle. For instance, a study focusing on a small local scale might capture only nearstream factors affecting microplastic pollution, which may differ from findings of a larger regional study that incorporates more distant and upstream regions (Grbić et al., 2020). From a temporal standpoint, microplastic concentrations may also vary between the event scale (e.g., a storm event and subsequent flooding) versus repeated samplings over the course of several seasons (Cheung et al., 2019; Stanton et al., 2020). In summation, these various scales of analyses include variations in spatial scale (e.g., river reach, full watershed scale) as well as temporal scale (e.g., sampling over the course of several hours, repeated seasonal samplings).

Given the above considerations, the main objectives of this review are to: (i) evaluate the influence of watershed attributes such as land cover, population density, and physical watershed/stream characteristics on microplastic abundances, (ii) examine the influence of seasonality, precipitation, and flow rate on microplastic abundances, and (iii) discuss the role of scale with regard to the distribution and identification of microplastics.

A literature search was conducted in the Web of Science database and included peer-reviewed journal articles published through June 2021. The search string was "microplastic*" and ("freshwater*" or "river*" or "stream*" or "lake*"). A total of 1149 articles were produced, of which 75 were included for the purposes of this review paper. Papers were excluded for the following reasons: an exclusive focus on microplastics and organisms, laboratory studies, modeling studies, review papers, a general focus on plastics (not specifically microplastics), no apparent statistical analyses of spatial/temporal factors affecting microplastics, and no spectroscopic microplastic verification (e.g., μFTIR, Raman).

As previously mentioned, it is not uncommon for research publications to note a size range of 1 μm-5mm for microplastic particles. However, not all of the reviewed studies included microplastics spanning this particular range. For instance, studies commonly varied with regard to the lower size boundary, which was often due to factors such as differing net mesh sizes during sample collection. Those using a larger mesh, such as the commonly used 333 μm mesh plankton net, were unable to capture and quantify microplastics falling into smaller size ranges (Campanale et al., 2020; Constant et al., 2020; Hoellein et al., 2017; McCormick et al., 2014; Yonkos et al., 2014). Smaller classes of microplastics were captured with the employment of other methods, such as the use of smaller mesh nets or grab samples when collecting microplastics in surface waters (Stanton et al., 2020; Xia et al., 2020; Zhao et al., 2020), or by collecting sediment samples and using smaller mesh sieves (Corcoran et al., 2020a; Hurley et al., 2018; Sarkar et al., 2019). Thus, the lower size limit of observed microplastics differed among studies as a function of data collection methodologies.

2. Factors affecting the spatial distribution of microplastics

Spatial distributions of microplastics may be influenced by a variety of factors, including those relating to anthropogenic activities as well as physical watershed/stream characteristics. Previous empirical studies have focused on the impacts of anthropogenic activities such as land cover, wastewater treatment plants, and population density on microplastic abundances. While various physical watershed characteristics (e.g., elevation, slope) may also influence microplastic abundances, very few studies have directly addressed these links. Nevertheless, these will be included in the following discussion and highlight the need for additional research in this area. Table 1 shows positive and negative relationships between microplastics and both anthropogenic activities and physical watershed characteristics. A total of 35 publications reported significant results regarding such factors, and microplastic concentrations in these studies may thus be considered spatially dependent.

2.1. Urban land cover

Previous studies have shown strong links between microplastic pollution in freshwater bodies and specific land cover categories (Chen et al., 2020). In particular, urban land cover is closely correlated with microplastic abundance (de Carvalho et al., 2021; Feng et al., 2020; Su et al., 2020; Sang et al., 2021), potentially due to factors such as insufficient waste management strategies and littering (Battulga et al., 2019; Mani and Burkhardt-Holm, 2020). Elevated levels of microplastics have been observed in watersheds characterized by a high proportion of urban land cover (Grbić et al., 2020; Nihei et al., 2020; Yonkos et al., 2014), and have been found in higher concentrations with increasing proximity to urban or industrial centers (Ding et al., 2019; Huang et al., 2021; Luo et al., 2019; Wang et al., 2017) (Table 1). Watersheds characterized by active industrial zones have been linked with elevated microplastic concentrations in their freshwater bodies (Chen et al., 2020; Corcoran et al., 2020b; Deng et al., 2020; Feng et al., 2020; Grbić et al., 2020; Lahens et al., 2018; Li et al., 2020b; Liu et al., 2020). Such results indicate that microplastic abundances are heavily influenced by proximity to anthropogenic activities.

It is less common for studies to report no significant correlation (Barrows et al., 2018, Belen Alfonso et al., 2020; Mai et al., 2021; Wang et al., 2020) or a negative relationship between microplastic concentrations and urban land cover (He et al., 2020b; Yin et al., 2020). Of the studies focusing on urban land cover, 33.3% of running water studies reported no significant relationship, with just one disclosing a negative relationship (He et al., 2020b). For still water studies, three reported no significant relationship (30%), and one reported a negative relationship (Yin et al., 2020) (Table 1). Negative correlations may potentially be due to strict local regulations regarding pollution (Liu et al., 2020) or to waste management strategies that greatly surpass those found at rural sites (Yin et al., 2020). Additionally, lack of a correlation could potentially be due to high rates of atmospheric deposition of microfibers over all land cover categories within a study region, thus obfuscating connections between urbanization and microplastics (Kaliszewicz et al., 2020). In certain instances, microplastic abundances may be higher in urban areas but the correlation is not significant, indicating the potential for additional influential factors (Mai et al., 2021). Future research could incorporate a focus on relationships between land use and specific microplastic type, as correlations between these factors could potentially be stronger than those between land use and microplastic abundance (He et al., 2020b).

Recent research has also evaluated the role that roads and the transportation industry may play in freshwater microplastic pollution, with initial results showing vehicle tire particles present in samples (Grbić et al., 2020). Additionally, positive relationships have been found between microplastics and total road length at both the catchment scale and the riparian zone scale (Grbić et al., 2020).

2.2. Wastewater treatment plants

Urban and industrial regions are often home to wastewater treatment plants (WWTPs), which have been closely linked to microplastic pollution (Grbić et al., 2020; Shruti et al., 2019) (Table 1). More specifically, microplastic abundances are often higher at sites downstream of WWTPs (Hoellein et al., 2017; Liu et al., 2020; Schmidt et al., 2018; Shruti et al., 2019), with one estimate showing microplastic abundances at sites downstream of WWTPs exceeding those at upstream sites by a factor

Table 1
Spatial factors affecting MP concentrations in freshwater. Percentages in parentheses refer to the relative number of articles (as a function of either still water or running water) that assessed correlations with spatial factors.

	Lakes/reservoirs/wetlands			Running water		
Explanatory factors	Positive	Nega-tive	No relation	Positive	Negative	No relation
Human activities						
Urban land cover	Corcoran et al., (2020b), Deng et al., (2020), Di and Wang (2018), Feng et al., (2020), Liu et al., (2019a), Wang et al., (2017) (60%)	Yin et al., (2020) (10%)	Belen Alfonso et al., 2020, Kaliszewicz et al., (2020), Liu et al., (2019b) (30%)	Alam et al., (2019), Chen et al., (2020), de Carvalho et al., (2021), Ding et al., (2019), Feng et al., (2020), Grbić et al., (2020), Huang et al., (2021), Kataoka et al., (2019), Lahens et al., (2018), Li et al., (2020b), Liu et al., (2020), Luo et al., (2019), Nihei et al., (2020), Peng et al., (2018), Sang et al., (2021), Schmidt et al., (2018), Su et al., (2020), Tibbetts et al., (2018), Yonkos et al., (2014) (63.3%)	He et al., (2020b) (3.3%)	Barrows et al., (2018), Battulga et al., 2019, Corcoran et al., (2020a), Huang et al., (2020), Jiang et al., (2019), Klein et al., (2015), Mai et al., 2021, Stanton et al., (2020), Wagner et al., (2019), Wang et al., (2020) (33.3%)
Wastewater treatment plant effluent	–	–	–	Grbić et al., (2020), Hoellein et al., (2017), Liu et al., (2020), McCormick et al., (2016), McCormick et al., (2014), Schmidt et al., (2018), Shruti et al., (2019) (58.3%)	–	Bujaczek et al., (2021), Klein et al., (2015), Peller et al., (2019), Stanton et al., (2020), Tibbetts et al., (2018) (41.7%)
Agricultural land cover	–	–	–	–	Grbić et al., (2020), Huang et al., (2020) (40%)	Barrows et al., (2018), He et al., (2020b), Nihei et al., (2020) (60%)
Population density	Bertoldi et al., (2021), Corcoran et al., (2020b) (40%)	–	Belen Alfonso et al., 2020, Feng et al., (2020), Mbedzi et al., (2020) (60%)	Battulga et al., 2019, Fan et al., (2019), Grbić et al., (2020), Huang et al., (2020), Kataoka et al., (2019), Mai et al., 2021, Nihei et al., (2020), Yonkos et al., (2014) (57.1%)	–	Dikareva and Simon (2019), Feng et al., (2020), Kapp and Yeatman (2018), Klein et al., (2015), Tibbetts et al., (2018), Zhou et al., (2020) (42.9%)
Physical						
Elevation	–	–	–	–	Su et al., (2020) (100%)	–
Slope	–	–	–	Grbić et al., (2020) (100%)	–	–
Water body width	–	–	–	–	–	de Carvalho et al., (2021) (100%)

greater than nine (McCormick et al., 2014). In these instances, smaller particles and fibers may not be captured by treatment processes and thus end up in effluent (McCormick et al., 2016). Because of this, high downstream concentrations of smaller microplastics in particular may indicate that WWTPs serve as a pathway for these plastics to freshwater environments.

While WWTPs are generally accepted as major delivery pathways of microplastics, the relationship between microplastics and effluent is not always so clearly defined. Some analyses (41.7%) have not found correlations between the two (Bujaczek et al., 2021; Klein et al., 2015; Peller et al., 2019; Stanton et al., 2020; Tibbetts et al., 2018) (Table 1). One potential explanation is that nets with larger mesh sizes do not capture smaller microplastics (Dris et al., 2015), and consequently may not produce evidence of a relationship between microplastics and effluent. Additionally, higher microplastic loads upstream of WWTPs may be due to downstream dilution resulting from the release of effluent (Tien et al., 2020). Lastly, the influence of WWTPs on downstream microplastic concentrations may also depend upon the specific wastewater treatment processes, with tertiary treatments typically more successful in removing microplastics (Bujaczek et al., 2021; McCormick et al., 2016). Such results may indicate that WWTPs should not necessarily be generalized as main sources or pathways of microplastics. While effluent may certainly exert an influence, microplastic sources in freshwater bodies are very diverse (Huang et al., 2020), and other attributes may overshadow the role of effluent in certain situations (Bujaczek et al., 2021; Tien et al., 2020). Indeed, the lack of a correlation between microplastics and effluent led Klein et al. (2015) to conclude that hydrodynamic processes may in fact play a more important role in the distribution of microplastics. In light of this theory, an important avenue for future research may include the influence of such microscale variations on microplastic pollution.

2.3. Agricultural land cover

Links between microplastic pollution and agricultural regions are also not clearly defined, with some studies (40%) reporting lower abundances in these zones than in other land use categories (Grbić et al., 2020; Huang et al., 2020) (Table 1). This negative relationship may be attributed to factors such as lower population densities in agricultural regions (Huang et al., 2020), or to the potential for agricultural soils to serve as a sink for plastic particles (Feng et al., 2020). Other studies (60%) report no significant correlations between microplastics and agricultural land use (Barrows et al., 2018; He et al., 2020b; Nihei et al., 2020), indicating that other factors may exert a stronger influence on microplastic pollution.

While negative or no relationships have been reported in studies examining links between microplastics and agricultural land use, more studies are needed to incorporate other variables related to agricultural practices. Microplastic-rich biosolids have been applied widely to agricultural lands as crop fertilizers, which can contaminate soils and runoff (Leslie et al., 2017). Additionally, plastic covers and tarps have been used to retain moisture and discourage weed growth in agricultural fields, which can break down and work their way into the environment if not collected immediately after harvest (Feng et al., 2020). Therefore, it is important to understand the transport pathways of such microplastics to soils and streams. Exploring these connections and focusing on the proper management of agricultural lands should be a high priority in future research (Ding et al., 2019).

2.4. Microplastics in remote regions

Additional research has supported the trend of decreased microplastic concentrations at sites located further in proximity from urban and industrial regions (Di and Wang, 2018; Grbić et al., 2020; Huang et al., 2021; Peng et al., 2018; Su et al., 2020; Tibbetts et al., 2018; Yonkos et al., 2014). This may be the case particularly in forested regions (Grbić et al., 2020) and in water bodies located near nature preserves or natural areas (Huang et al., 2021). However, water bodies in these regions have still been found to contain microplastics. While microplastic concentrations generally decrease at sites far from anthropogenic activities, microplastics have been found in historically pristine regions as well, despite no nearby industrial or developed regions (Jiang et al., 2019).

High levels of microplastics in these regions may be due to heavy tourist activities, resulting in increased littering (Feng et al., 2020) and the transfer of plastic wastes to more remote downstream locations. Recreation and tourism may thus potentially serve as important sources of microplastics (Barrows et al., 2018; Feng et al., 2020), as can fishing and fishery activities, as nets and fishing lines degrade over time and remain in freshwater environments (Belen Alfonso et al., 2020; Di and Wang, 2018; Xia et al., 2020). Wind may also serve as a critical large-scale transport mechanism by carrying microplastics from developed regions to more remote ones (Jiang et al., 2019), thus underscoring the importance of atmospheric deposition. These findings are pivotal to microplastics research, as they indicate that potentially no body of water is immune to microplastic pollution.

2.5. Population density

Population density is often tied to microplastic pollution in freshwater bodies, with numerous studies finding positive correlations between the two (Battulga et al., 2019, Bertoldi et al., 2021, Corcoran et al., 2020b, Fan et al., 2019, Grbić et al., 2020, Huang et al., 2020, Kataoka et al., 2019, Mai et al., 2021, Nihei et al., 2020, Yonkos et al., 2014) (Table 1). High microplastic concentrations may be found in waters adjacent to regions characterized by high population density for a number of reasons. Fibers in particular are produced by the laundering of synthetic materials, subsequently making their way into washing machine effluent (McCormick et al., 2016; Peller et al., 2019). Direct laundering of clothing in rivers can also be key in introducing microplastics to freshwater environments (Alam et al., 2019). Additionally, pellets found in personal care products such as exfoliants often show up in household sewage (McCormick et al., 2016). Links have been found between residential zones and microplastic concentrations (Sang et al., 2021), with domestic sewage, new residence construction, and roads contributing microplastics to aquatic environments (Dikareva and Simon, 2019). Additionally, recent research has found positive links between microplastic pollution and gross domestic product (Fan et al., 2019; Huang et al., 2020; Zhou et al., 2020), highlighting the potential for socio-economic factors to play a role in the presence and prevalence of microplastics.

Other research has not shown clear connections between microplastics and population density (Belen Alfonso et al., 2020; Feng et al., 2020; Kapp and Yeatman, 2018; Klein et al., 2015; Mbedzi et al., 2020; Tibbetts et al., 2018; Zhou et al., 2020) (Table 1). As a potential explanation, Dikareva and Simon (2019) suggested that previous reported links between the two may be due to study designs of a "coarse manner with a limited number of sites," or to designs that encompass sites representing only population density extremes. Thus, the degree to which a broad population density gradient is represented may exert an influence on observed microplastic concentrations, in addition to factors such as the total number of study sites and number of samplings (Belen Alfonso et al., 2020; Dikareva and Simon, 2019). Additionally, population density may serve as a stronger driving force for microplastic pollution when considered in tandem with other factors, such as seasonality. For instance, activities conducted in a populous region may change across seasons, resulting in a significant interaction effect between seasonality and population density (Mbedzi et al., 2020).

2.6. Physical watershed/stream characteristics

While many studies have addressed links between microplastic pollution and the influence of anthropogenic activities, very few have examined the role of physical watershed characteristics and geomorphology (Table 1). For instance, increased slope of the riparian zone can lead to elevated microplastic abundances in surface water samples (Grbić et al., 2020). In addition, Su et al. (2020) found higher microplastic concentrations in Australian water bodies located at lower elevations (Table 1). Very little data exist regarding whether water body width may influence microplastic accumulation, with initial research not finding statistically significant relationships between these variables (de Carvalho et al., 2021). The above findings indicate the potential for small-scale physical features of watersheds to exert an influence on microplastic accumulation and abundance. However, the limited number of studies addressing such factors indicates that more research is needed.

These results also highlight the variations in microplastic distributions between sediment and water samples. Generally speaking, polymers with densities less than that of water (e.g., polypropylene, polyethylene) are more buoyant and are often found in the upper levels of the water column in calm waters (Di and Wang, 2018; Wang et al., 2020). Polymers whose densities exceed that of water (e.g., polyethylene terephthalate, polyvinyl chloride) are more apt to sink and settle on the channel bottom (Wang et al., 2020). However, more than half of the studies in running water did not examine microplastics in sediment, while nearly two-thirds of studies in still water investigated sediment samples (Fig. 3).

Additionally, there may exist a relationship between sediment grain size and microplastic abundance. More specifically, small-grained sediments and sand may be linked with greater numbers of microplastics, due to the ability of both to settle out of the water column in lower velocity flows (Corcoran et al., 2020a; He et al., 2020b; Dikareva and Simon, 2019; Sarkar et al., 2019; Tibbetts et al., 2018). Conversely,

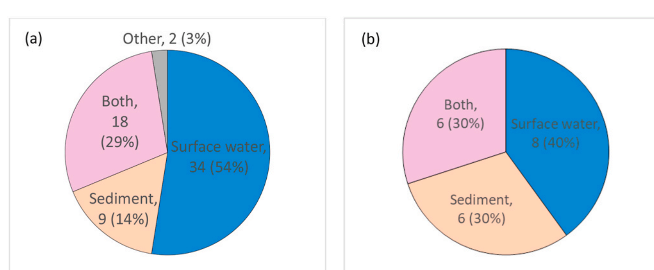

Fig. 3. Number of publications addressing microplastic concentrations in surface water, in sediment, or in both. (a) represents studies addressing microplastics in running water (e.g., rivers, streams), and (b) represents those addressing microplastics in still water (e.g., lakes, ponds). Several studies sampled both running water and still water, and are thus represented in both (a) and (b). Note: The study falling into the "Other" category involved the collection of visible plastic debris on shores, which contained microplastics (Battulga et al., 2019), or the collection of pellets on shores (Corcoran et al., 2020b).

fewer microplastics have been found at sites characterized by coarser sediments and higher flows (Tibbetts et al., 2018).

3. Factors affecting the temporal distribution of microplastics

Microplastic abundances vary on a temporal basis, which can be attributed to both hydroclimatic and hydrodynamic factors, as well as the frequency of sampling. Previous studies have focused on the impacts of precipitation, runoff, and flow rate on microplastic distributions and abundances. Table 2 shows the positive and negative relationships between microplastics and these factors, and includes 26 studies that found significant correlations. These studies indicated temporal dependence of microplastic concentrations (i.e., these studies reported significant findings with regard to temporal factors such as seasonality, precipitation, stormflow, or flow rate/discharge). Six studies indicated both spatial and temporal dependence (Chen et al., 2020; de Carvalho et al., 2021; Fan et al., 2019; Grbić et al., 2020; Sang et al., 2021; Schmidt et al., 2018) (Table 1).

3.1. Effects of precipitation seasonality on microplastic concentrations

Microplastic concentrations are influenced by factors intrinsic to the changing seasons, particularly with regard to precipitation (Xia et al., 2020). Precipitation may serve to transport land-based microplastics into aquatic environments, and high abundances of microplastics in surface waters have been observed following such rain events (Schmidt et al., 2018; Wong et al., 2020; Xia et al., 2020). In particular, precipitation may lead to a first flush event, in which microplastics that have accumulated on land during dry periods are flushed into freshwater environments in the early wet season (Schmidt et al., 2018). In this vein, antecedent precipitation may strongly influence observed concentrations of microplastics. For instance, rain events preceded by dry periods lasting several weeks can result in significantly higher microplastic levels than samples collected during the dry period, with similar yet muted results regarding microplastic samples collected after a rain event preceded by a week-long dry period (Schmidt et al., 2018). These findings suggest that dry periods may facilitate the accumulation of microplastics on land-based surfaces, with subsequent rain events flushing them into nearby rivers and streams (Schmidt et al., 2018).

The vast majority of a river's annual surface water microplastic load may be directly linked with the wet season (Eo et al., 2019), likely a product of increased runoff introducing microplastics to receiving waters as well as the resuspension of microplastics from benthic sediments (Hurley et al., 2018; Xia et al., 2020) (Table 2). It is thus not uncommon to observe significant differences in microplastic abundances between the wet and dry seasons, with indications that higher abundances in surface waters are present in the wet season (Campanale et al., 2020; Eo et al., 2019). However, these trends may not necessarily pertain to microplastics in sediment. For instance, lower concentrations of microplastics in river sediments following major flooding events indicate that floods may flush and resuspend microplastics from aquatic sedimentary environments (Hurley et al., 2018; Liu et al., 2019c). In addition, higher microplastic abundances in sediment than surface water may be present during the dry season, due to low flow facilitating the settling out of microplastics into sediment (Eo et al., 2019; Liu et al., 2019c; Mbedzi et al., 2020).

It is also suggested that such disparities exist between sediment and surface water microplastics due to more intense microplastic fluctuations in surface water. Microplastics may remain trapped in sediments for longer periods of time and thus represent more long-term concentrations (Ding et al., 2019). An examination of stormwater retention ponds in Denmark identified significant relationships between microplastic concentrations in water samples and land use categories (Liu et al., 2019a), yet when evaluating sediment samples from these same retention ponds, Liu et al. (2019b) found no evidence of such relationships. Because of such disparities, it is not uncommon for analyses to find no correlations between surface water and sediment samples regarding observed microplastic abundances (Constant et al., 2020; Deng et al., 2020; Li et al., 2020b), or to find that abundances between the two are not proportional (Di and Wang, 2018; Ding et al., 2019).

Microplastic abundances may also vary as a function of the type of sediment sampled. For instance, Hengstmann et al. (2021) reported substantial differences in microplastic abundances found in lakeshore sediments between seasons, with no such seasonal trend observed for lakebed sediments. Such a finding may result from the tendency for benthic sediments in particular to serve as a sink for microplastics (He et al., 2020a; Hengstmann et al., 2021).

Some studies do not report significant links between microplastics and seasonality (Chanpiwat and Damrongsiri, 2021; Constant et al., 2020; Mani and Burkhardt-Holm, 2020; Mintenig et al., 2020; Stanton

Table 2
Temporal factors affecting MP concentrations in freshwater. Percentages in parentheses refer to the relative number of articles (as a function of either still water or running water) that assessed correlations with temporal factors.

Explanatory factors	Lakes and reservoirs			Running water		
Hydroclimatic factors	Positive	Negative	No relation	Positive	Negative	No relation
Wet season	–	Liu et al., (2019c), Mbedzi et al., (2020), Wang et al., (2021) (60%)	Hengstmann et al., 2021 [a], Su et al., (2016) (40%)	Campanale et al., (2020), Chen et al., (2020), Eo et al., (2019), He et al., (2020a) (23.5%)	Barrows et al., (2018), de Carvalho et al., (2021), Fan et al., (2019), Wang et al., (2021), Weideman et al., (2020), Wu et al., (2020) (35.3%)	Chanpiwat and Damrongsiri (2021), Constant et al., (2020), Mani and Burkhardt-Holm (2020), Mintenig et al., (2020), Peller et al., (2019), Stanton et al., (2020), Zhao et al., (2020) (41.2%)
Precipitation	Xia et al., (2020) (50%)	–	Belen Alfonso et al., 2020 (50%)	Piñon-Colin et al., (2020), Schmidt et al., (2018), Wong et al., (2020) (50%)	–	Constant et al., (2020), de Carvalho et al., (2021), Mani and Burkhardt-Holm (2020) (50%)
Storm runoff	–	–	–	Cheung et al., (2019), Grbić et al., (2020), Piñon-Colin et al., (2020), Sang et al., (2021) (80%)	Hurley et al., (2018) (20%)	–
Flow velocity/ discharge	–	–	–	Campanale et al., (2020), Mani and Burkhardt-Holm (2020), Wagner et al., (2019) (23.1%)	Barrows et al., (2018), de Carvalho et al., (2021), Kapp and Yeatman (2018), Sarkar et al., (2019), Tien et al., (2020), Xiong et al., (2019) (46.1%)	Bujaczek et al., (2021), Constant et al., (2020), Dris et al., (2018), Lechthaler et al., (2021) (30.8%)

[a] Indicates microplastic concentrations in lakebed sediments.

et al., 2020; Su et al., 2016). Additionally, negative or no relationships have been reported between microplastics and precipitation, indicating the potential for storm events and flooding to dilute microplastic concentrations in surface waters (Barrows et al., 2018; de Carvalho et al., 2021; Fan et al., 2019; Stanton et al., 2020). Increased abundances of microplastics in surface waters have also been reported during the dry season (de Carvalho et al., 2021; Fan et al., 2019; Wang et al., 2021; Weideman et al., 2020; Wu et al., 2020). These findings may be a result of microplastics being more heavily influenced by anthropogenic as opposed to environmental variables (Mani and Burkhardt-Holm, 2020), or the potential for microplastics to vary more strongly as a function of spatial rather than temporal factors (Mintenig et al., 2020). Physical characteristics of microplastics (e.g., size, shape) may also play a role, in that smaller microplastics may remain in the upper water column during periods of low flow (de Carvalho et al., 2021). With varying results regarding the influence of seasonality and precipitation, future research is needed to address microplastic pollution at finer temporal and spatial resolutions.

3.2. Effects of storm runoff on microplastic concentrations

As previously noted, these findings suggest that stormwater runoff plays a critical role in delivering microplastics to freshwater bodies (Cheung et al., 2019; Grbić et al., 2020; Piñon-Colin et al., 2020; Sang et al., 2021) (Table 2). Higher precipitation rates have been correlated with increased microplastic pollution in stormwater runoff, potentially due to factors such as the flushing of discarded plastics into pipelines during storm events (Sang et al., 2021), as well as combined sewer overflows (Piñon-Colin et al., 2020). Indeed, these overflows may serve as critical transport pathways to aquatic environments. While few studies incorporate a focus on combined sewer overflows, preliminary research shows elevated abundances of microplastics in overflows, even exceeding those found in WWTP effluent (Chen et al., 2020). Future research should closely address this potentially critical link with microplastics pollution. The above results suggest that runoff may serve as a major delivery pathway of microplastics, by both introducing land-based plastics to freshwater bodies (Sang et al., 2021) as well as facilitating the delivery of microplastics to estuarine or marine environments (Zhao et al., 2020).

Selecting appropriate sampling times may be critical in evaluating the effects of rainfall and runoff on microplastics, as abundances can fluctuate greatly over relatively short periods of time. For instance, Cheung et al. (2019) sampled after a storm event and reported that microplastic concentrations decreased dramatically over the course of just 2 h, and continued to decrease substantially with further samplings. Microplastic pollution is thus very closely tied to runoff processes, which can lead to quick variations in microplastic concentrations (Cheung et al., 2019; Hurley et al., 2018). As few studies incorporate an in-depth examination of microplastic concentrations over the course of a single rainfall event, additional fine temporal-scale research is needed when evaluating the role of precipitation and runoff. Knowing when these concentrations tend to be higher can provide insight regarding potential delivery pathways to riverine environments, which can assist in informing management decisions concerning microplastic waste.

3.3. Effects of flow on microplastic concentrations

There is evidence that microplastics are influenced by water velocity, in that lower flow rates and weakened hydrodynamics may facilitate their accumulation (Barrows et al., 2018; de Carvalho et al., 2021; Kapp and Yeatman, 2018; Sarkar et al., 2019; Tien et al., 2020; Xiong et al., 2019) (Table 2). For instance, lower microplastic concentrations have been observed in the center of river channels themselves (Corcoran et al., 2020a; Tibbetts et al., 2018), with greater numbers of microplastics found along river banks (Dris et al., 2018). Interestingly, Wagner et al. (2019) found a positive correlation between microplastic concentrations and discharge in urban subwatersheds in Germany, with no such relationship in rural subwatersheds. The positive relationship may have been due to inputs from combined sewer overflows (Wagner et al., 2019). It is less common for studies to show no relationship between flow rate/discharge and microplastic concentrations (Bujaczek et al., 2021; Dris et al., 2018; Lechthaler et al., 2021).

As a function of both spatial and temporal variables, microplastic concentrations are highly heterogeneous within a given river (Kataoka et al., 2019; Stanton et al., 2020). These factors can greatly influence the number of microplastics that are delivered to aquatic environments, as well as the degree to which in-stream processes facilitate or hinder accumulation. Variations in seasonal microplastic abundance and distribution is at least partially a function of hydrologic variables (Campanale et al., 2020; de Carvalho et al., 2021; He et al., 2020a). If such processes are intense, microplastics are less apt to settle or to remain trapped in sediment, and are more likely to become suspended in the water column (Luo et al., 2019). Slower flow rates may lead to the accumulation of microplastics in sediments and at lower depths in the water column, as these conditions facilitate the settling of microplastics (Tien et al., 2020). In this sense, streams and rivers have the potential to serve as microplastic sinks, with microplastic concentrations varying based on the time of year. Thus, instead of being continually transported along the length of a river, they can remain trapped in sediment until a rain event occurs and spurs their resuspension (Hurley et al., 2018).

4. The role of scale

Scale may play an important role when evaluating the distribution of freshwater microplastics, and the studies selected for this review focused on a variety of spatial and temporal scales. As shown in Fig. 4a, some specific hydrological and anthropogenic processes may dominate microplastic concentrations at specific spatial and temporal scales. From a spatial perspective, these analyses range from a single point source or river reach to the study of watersheds at a national level. From a temporal perspective, they range from a single sampling session to annual sampling sessions. As shown in Fig. 4b, a majority of studies examined microplastic concentrations using a snapshot approach rather than a range of scales. In particular, only a few studies investigated a longer term with a larger spatial extent.

Some studies examined microplastic pollution as a function of watershed-scale attributes such as land use and population density (Grbić et al., 2020; Su et al., 2020; Yonkos et al., 2014). However, Dikareva and Simon (2019) argued that such attributes fail to fully explain variations in microplastic distributions, and that a focus on local-scale attributes is just as crucial. In particular, an emphasis on specific point sources (e.g., plastic production facilities and dumping sites) of microplastic pollution may provide valuable insight regarding variations in microplastic concentrations (Dikareva and Simon, 2019). Similarly, Barrows et al. (2018) noted that analyses at the larger watershed scale may not provide a comprehensive picture of microplastic pollution and corresponding sources, and that future study designs may benefit from incorporating a focus on individual or specific sources of pollution. However, a sole focus on such point sources excludes the influence of important nonpoint sources such as runoff (Cheung et al., 2019).

Finer temporal resolutions are also becoming increasingly imperative in more fully understanding the microplastic cycle (Grbić et al., 2020; Stanton et al., 2020). As previously mentioned, microplastic concentrations can vary quite drastically over smaller temporal intervals, whether these differences are observed over several weeks (Stanton et al., 2020), from one day to the next, (Xia et al., 2020), or even over the course of a few hours (Cheung et al., 2019). With microplastic fluctuations occurring with such a high frequency, it becomes increasingly difficult for studies focusing on larger temporal intervals to not only pinpoint sources, but also to estimate accurate microplastic fluxes (Stanton et al., 2020; Zhao et al., 2019).

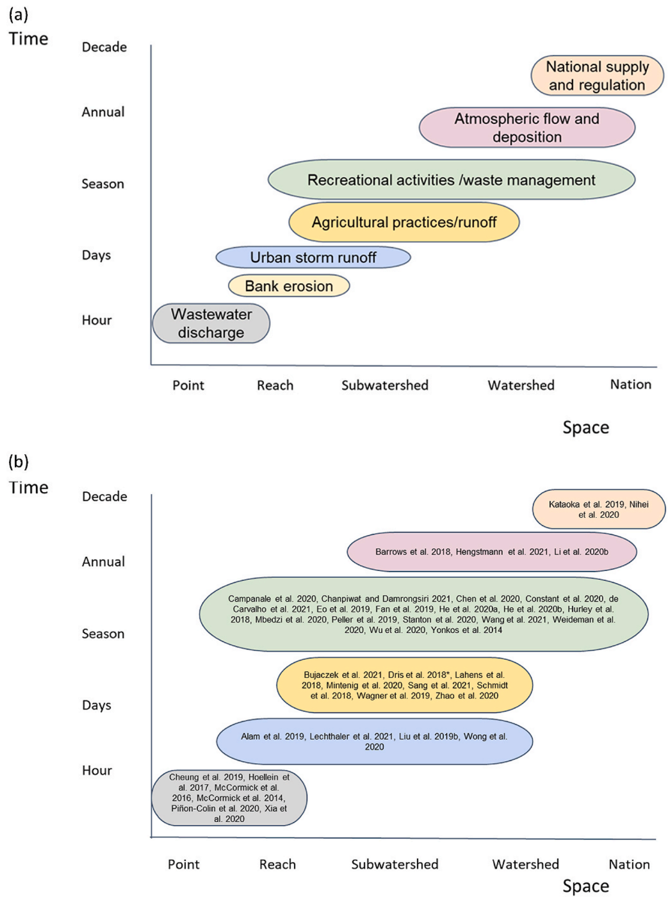

Fig. 4. Hydrological and anthropogenic processes affecting microplastic concentrations in freshwater environment (a) across a range of space and time scales and (b) exemplary case studies. Asterisks denote studies that included more than one spatial or temporal scale.

Additionally, few studies appear to explicitly define the spatial extent of contributing areas to microplastic pollution in freshwater bodies. The use of such well-defined scales and extents could greatly facilitate the comparison of results across studies, and allow for a greater understanding of the factors that influence the distribution and abundance of microplastic particles. For instance, this could include more specific spatial extents, such as the delineation of subwatersheds, the incorporation of riparian buffers, or the use of specific distances from study sites (Grbić et al., 2020; Wagner et al., 2019).

These variations in contributing areas may lead to differences in reported correlations, and different approaches may increase difficulty in evaluating the true impact of land cover on microplastic pollution. Some studies have used a specified radius around urban centers in the classification of urban sites, with sites exceeding this distance designated as rural (Corcoran et al., 2020a). In a similar vein, various radii around study sites have been incorporated to assess the impact of other watershed attributes such as population density (Tibbetts et al., 2018). Other studies have calculated the proportion of various land use categories within watersheds (Barrows et al., 2018; Kataoka et al., 2019), with the delineation of subwatersheds upstream of study sites used in the evaluation of watershed attributes (Nihei et al., 2020; Su et al., 2020; Wagner et al., 2019). The use of such differing techniques highlights the need for standardized spatial analysis methodologies.

Interestingly, only one study noted the use of a riparian buffer, and this was used in conjunction with analyses conducted at the full watershed level (Grbić et al., 2020). While the latter analyses produced negative correlations between microplastics and agricultural land covers, and analyses at the riparian scale showed a positive relationship between microplastics and slope in the buffer zone, there were few differences present between the two methods (Grbić et al., 2020). More research is needed at a broader range of scales to better understand the impacts on microplastic pollution.

Additionally, distance-weighted algorithms recently developed in spatial hydrology can offer new insights on sources and delivery pathways of microplastics in freshwater environments (Mainali et al., 2019). Different scales of analyses can capture different factors that are linked with freshwater contamination, with Mainali et al. (2019) noting that a major upstream source of contamination may not be identified in an analysis that focuses solely on a stream's riparian zone. Conversely, explanatory variables more closely correlated with proximity to a water body (e.g., topographic factors such as slope) may be overlooked in an analysis that incorporates the full watershed scale.

The scale-dependent processes could also vary along urbanization or flow gradient (Fig. 5). This figure outlines conditions for which either microscale or large-scale processes may dominate in driving microplastic concentrations in freshwater environments, with microplastic pollution shown as a function of both flow rate and anthropogenic activities. For example, microplastic concentrations may be more subject to microscale processes resulting from spatial heterogeneity in the urban environment during low flow season. There may be lower input from terrestrial sources, and increased microplastic concentrations may be particularly apparent in riverine sediment (Hoellein et al., 2017).

Conversely, upstream processes may become more important for determining microplastic concentrations during the high flow season, in which microplastics may either increase due to increased transport (i.e., runoff) to freshwater environments (Campanale et al., 2020) or decrease due to dilution effects (Fan et al., 2019). These large-scale processes may also be more important in regions characterized by fewer anthropogenic activities, as atmospheric sources may play a more critical role (Jiang et al., 2019). Thus, the most appropriate scale for a given study may vary depending upon the study goals. For instance, Hoellein et al. (2017) discussed the need for larger scales when investigating issues pertaining to deposition, and smaller scales for research centered around factors pertaining to microplastics distribution in riverbed sediments.

Tailoring the analytical approach to the study region may also be a worthwhile pursuit, in that multiscale analyses or distance-weighted algorithms may shed further light on microplastic sources and pathways in different environments. For instance, urban environments are comprised of a broad range of potential plastic sources, in terms of both specific point sources as well as nonpoint sources such as runoff (Deng et al., 2020; Piñon-Colin et al., 2020). In such environments, it may be critical to more fully address spatial heterogeneity (Mani and Burkhardt-Holm, 2020; Mintenig et al., 2020) than in remote regions characterized by fewer anthropogenic activities. The use of an inverse

Fig. 5. Dominant scale processes as a function of urbanization and flow gradients. The picture in each quadrant represents the combination of flow rate and anthropogenic activities present for each condition. For instance, the lower right quadrant represents low flow conditions in a region characterized by anthropogenic activities, and is represented by stagnant water in an urban area with high levels of visible plastic pollution.

distance-weighted technique, a common method employed in water quality studies (Mainali et al., 2019), was not observed in any of the reviewed studies.

5. Summary and future research directions

As research in the field of freshwater microplastics is still in the developing stages, much is still unknown regarding their spatiotemporal distributions and links to potential sources. It is much more common for studies to examine microplastic concentrations as a function of either spatial or temporal factors, with very few addressing both and across scales. It is also imperative that standard sampling procedures are developed, to ensure consistency of microplastics research as well as to facilitate cross-study comparisons. For instance, a range of net mesh sizes are currently employed when collecting microplastics in surface water, and a standard size would be ideal. Preferably these nets would include a very small mesh to capture tinier microplastics, which tend to greatly outnumber larger size categories (Chen et al., 2020; Fan et al., 2019; Schmidt et al., 2018). Additionally, replicates should be collected to capture within-site microplastic variability.

More research is needed concerning microplastic concentrations as a function of seasonality, particularly regarding variations within the wet season. Differences likely exist between microplastic concentrations in the early versus the late wet season due to factors such as the flush effect and flow dependency, and our understanding of the drivers of microplastic abundance would greatly benefit from more fine-scale temporal research. Future study designs should incorporate evaluations of microplastic variations across very short time periods (e.g., minutes/hours) as well as evaluations spanning multiple years and seasons, to more thoroughly investigate the range of factors influencing microplastic fluctuations over time. As previously noted, sample collection in surface water or sediment can greatly affect observed microplastic concentrations as well as morphologies and polymer types (Di and Wang, 2018; Hoellein et al., 2017). Thus, future studies can include the collection of microplastic samples in both sediment and surface waters to obtain a more comprehensive picture of microplastic pollution within a freshwater environment.

Additionally, few studies incorporate a focus along an urban-rural gradient (Chen et al., 2021), or address the effects of landscape fragmentation on microplastic distributions. Such analyses could reveal potential sources and delivery pathways of microplastic pollution, and GIS analyses could be incorporated into future study designs to facilitate our understanding of direct relationships between microplastic pollution and various watershed characteristics. Future research could also more thoroughly address the drivers of microplastic abundance, including the role of resuspension of sediments as well as flush effects from storm events. Very little is also known regarding microplastic pollution in groundwater, and future research could address how these abundances compare to surface water and sediment microplastic concentrations. Lastly, very few studies have addressed potential relationships between microplastics and physical characteristics such as slope, elevation, and river morphologies, and this is thus an area ripe for future research.

Generally speaking, it is not uncommon for speculations to be made with regard to potential microplastic sources and links with watershed attributes, as specific sources can be quite difficult to identify and can encompass a broad range (Huang et al., 2020). While many studies may speculate regarding potential ties with variables such as urban land cover or population density, more definitive trends may not be known or examined, and this appears to be the case for both spatial and temporal analyses. Plastic pollution is becoming an increasingly serious global issue, particularly during the COVID-19 era, in which the widespread use of disposable face masks and other personal protective equipment, increase in take-away plastic containers and utensils from restaurants, and uptick in the ordering of online products has resulted in greater plastic waste (Ammendolia et al., 2021; Mai et al., 2021). It is thus imperative for future research to incorporate more testing and statistical analyses regarding potential explanatory variables derived from a range of scales.

While some studies note atmospheric deposition as a possible explanation for elevated microplastic levels (Jiang et al., 2019; Liu et al., 2019b; Stanton et al., 2020), very few studies have incorporated the collection of such samples into their analyses. It is a growing area of research, and initial results suggest that microplastics deposited via this pathway may be much greater than observed concentrations in rivers (Brahney et al., 2020; Constant et al., 2020; Rochman and Hoellein, 2020). Standardization of practices and methodologies across space may facilitate the ability to more definitively address these concerns and understand the microplastic cycle.

Evaluating microplastic concentrations is a pressing global environmental issue, and collaborations will be crucial in alleviating it (Borrelle et al., 2020; Gong and Xie, 2020). Due to the wide array of sampling techniques, procedures and reporting units, it will additionally be imperative to create standardized methodologies to facilitate comparisons across studies (Campanale et al., 2020; Li et al., 2020a). With clear evidence that microplastics are ingested by a range of aquatic species, they can enter the food chain and thus potentially be ingested by humans (Li et al., 2020a,b). Their hydrophobic surfaces facilitate the sorption of a variety of metals and contaminants, thus exacerbating the risk to aquatic organisms (Wang et al., 2020; Zhang et al., 2020). A thorough and timely examination of microplastic sources and abundances at a range of spatial and temporal scales is therefore critical in developing policies and management procedures to reduce their release to the environment and minimize such negative consequences.

Credit author statement

Rebecca Talbot: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing - original draft, Writing – review & editing; Heejun Chang: Conceptualization, Supervision, Visualization, Writing - original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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